

Neutron star magnetospheres: the binary pulsar, Crab and magnetars

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Abstract. A number of disparate observational and theoretical pieces of evidence indicate that, contrary to the conventional wisdom, neutron stars' closed field lines are populated by dense, hot plasma and may be responsible for producing some radio and high energy emission. This conclusion is based on eclipse modeling of the binary pulsar system PSR J0737-3039A/B (Lyutikov & Thompson 2005), a quantitative theory of Crab giant pulses (Lyutikov 2007) and a number of theoretical works related to production of non-thermal spectra in magnetars through resonant scattering. In magnetars, dense pair plasma is produced by twisting magnetic field lines and associated electric fields required to lift the particles from the surface. In long period pulsars, hot particles on closed field lines can be efficiently trapped by magnetic mirroring, so that relatively low supply rate, *e.g.* due to a drift from open field lines, may result in high density. In short period pulsars, magnetic mirroring does not work; large densities may still be expected at the magnetic equator near the Y-point.

SECRET LIVES OF CLOSED FIELD LINES

Our understanding of pulsars is based on the Goldreich-Julian model [1], which postulates that pulsars are endowed with dipolar magnetic field; most magnetic field lines close back to the star, while those originating near the magnetic poles are open to infinity. All the action, like generation of radio and high energy emission, is assumed to take place on open field lines. Closed lines are assumed to be nearly dead, only carrying a particle density equal to the minimal charge density required by the electrodynamic conditions.

A number of recent observational and theoretical developments indicate that (at least in some parts of magnetosphere) the real particle density on closed field lines exceeds this minimal value by a large factor, of the order of $10^4 - 10^5$ and that these particles can produce radio and high energy emission, as we describe in these proceedings.

Eclipses in the double pulsar PSR J0737-3039A/B

In this system a fast recycled Pulsar A with period $P_A = 22.7$ msec orbits a slower but younger Pulsar B which has a period $P_B = 2.77$ sec in tightest binary neutron star orbit of 2.4 hours [2]. In addition to testing general relativity, this system provides a truly golden opportunity to verify and advance our models of pulsars magnetospheres, mechanisms of generation of radio emission and properties of their relativistic winds. This is made possible by a lucky fact that the line of sight lies almost in the orbital plane, with inclination less than half degree [3, 4]. Most strikingly, Pulsar A is eclipsed

once per orbit, for a duration of ~ 30 s centered around superior conjunction (when pulsar B is between the observer and pulsar A). The width of the eclipse is only a weak function of the observing frequency [5]. During the eclipse, the pulsar A radio flux is modulated by the rotation of pulsar B: there are narrow, transparent windows in which the flux from pulsar A rises nearly to the unabsorbed level [6]. These spikes in the radio flux are tied to the rotational phase of pulsar B, and provide key constraints on the geometry of the absorbing plasma. At ingress the transparent spikes appear at half rotational period of B, then change their modulation to rotational period of B at the middle of eclipse and disappear completely right before the egress (Fig 1). The physical width of the region which causes this periodic modulation is comparable to, or somewhat smaller, than the estimated size of the magnetosphere of pulsar B. Combined with the rotational modulation, this provides a strong hint that the absorption is occurring *within* the magnetosphere of pulsar B. This allows us to probe directly the structure of pulsar B magnetosphere.

The basis for understanding the behavior of the system is provided by the work [4], in which a model of A eclipses successfully reproduces the eclipse light curves down to intricate details, Fig. 1. The model assumes that radio pulses of A are absorbed by relativistic particles populating B magnetosphere through synchrotron absorption. The modulation of the radio flux during the eclipse is due to the fact that – at some rotational phases of pulsar B – the line of sight only passes through open magnetic field lines where absorption is assumed to be negligible. The model explains most of the properties of the eclipse: its asymmetric form, the nearly frequency-independent duration, and the modulation of the brightness of pulsar A at both once and twice the rotation frequency of pulsar B in different parts of the eclipse.

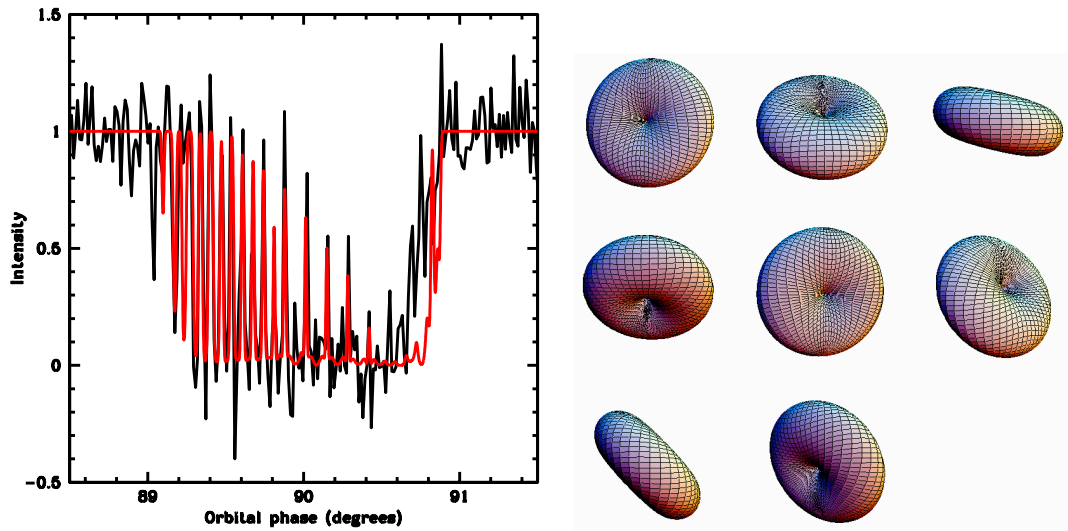


FIGURE 1. a. Comparison of a simulated eclipse profile (red) [4] with 800 MHz data (black) [6]. The model fits the data best in the middle of the eclipse, where distortions of B magnetosphere from the dipolar form by A wind are small. b. View of the magnetosphere at different rotational phases separated by $\pi/4$. For a full movie of the eclipse see <http://www.physics.mcgill.ca/~lyutikov/movie.gif>

This detailed agreement confirms the dipolar structure of the star's poloidal magnetic

field. One of the most interesting results is that closed field lines are populated with hot dense plasma, exceeding the minimal Goldreich-Julian density by a factor $\sim 10^5$. Presence of high multiplicity, relativistically hot plasma on closed field lines of pulsar B is somewhat surprising, but not unreasonable. Dense, relativistically hot plasma can be effectively stored in the outer magnetosphere, where cyclotron cooling is slow. The gradual loss of particles inward through the cooling radius, occurring on time scale of millions of pulsar B periods, can be easily compensated by a relatively weak upward flux driven by a fluctuating component of the current. For example, if suspended material is resupplied at a rate of one Goldreich-Julian density per B period and particle residence time is million periods, equilibrium density will be as high as $10^6 n_{GJ}$. The trapped particles either drift from open field lines or heated to relativistic energies by the damping of magnetospheric turbulence generated by A wind [4].

Crab giant pulses

Another important piece of information about the structure of pulsar magnetosphere and emission processes comes from a series of exceptional high time resolution observation of Crab pulsar at VLA [7]. Over the years the VLA pulsar group observed Crab giant pulses - exceptionally bright bursts of radio emission - with unprecedented temporal resolution reaching sub-nanosecond precision and corresponding large bandwidth. This, for the first time in decades, allows one to study elementary emission processes of enigmatic coherent emission mechanism of pulsars. To a great surprise, [7] identified unique features of GPs associated with the interpulse (IGPs) (Fig 2): (i) IGPs spectra consist of a number of relatively narrow frequency bands; (ii) spacing between the bands is proportional, $\Delta\nu/\nu \sim 0.06$; (iii) emission at different bands start nearly simultaneously, perhaps with a small delay at lower frequencies; (iv) sometimes there is a slight drift up in frequencies; all bands drift together, keeping the separation nearly constant; (v) emission bands are located at 4 – 10 GHz, continuing, perhaps, to higher frequencies, but *not* to lower frequencies; (vi) all IGPs show band structure.

These very specific properties allowed us to build a *quantitative* model of pulsar radio emission. The model actually does a fitting of pulsar spectra to a particular model [8], Fig. 2. The model places generation region of Crab giant pulses on closed magnetic field lines near the light cylinder (perhaps, this is the most striking features of the model, in stark contrast to all other models of pulsar radio emission). Waves are generated via anomalous cyclotron resonance in a set of fine, unequally spaced, narrow emission bands at frequencies much lower than a local cyclotron frequency. The model can reproduce the set of narrowband, unequally spaced emission bands seen in GHz frequency range in Crab giant pulses. We stress that this only applies to GPs, regular pulses are generated on open field lines, as is well established by a multitude of observational facts. We argue that giant pulses are different.

Waves are emitted at the anomalous cyclotron resonance

$$\omega - k_{\parallel} v_{\parallel} = s\omega_B/\gamma, \text{ for } s < 0 \quad (1)$$

where k_{\parallel} and v_{\parallel} are components of wave vector and particle's velocity along magnetic

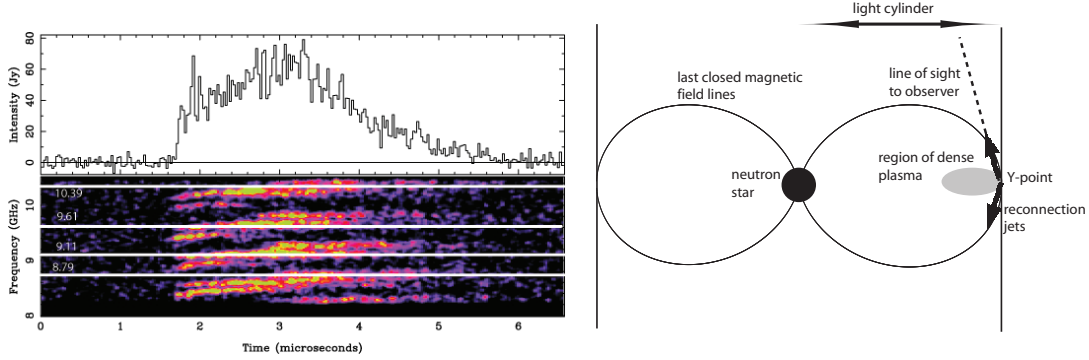


FIGURE 2. (a) Location of emission bands (white stripes) for the fiducial model. The fitted observations correspond to Fig. 4 of [7]. (b) Generation region of giant pulses in Crab. High density plasma is trapped on closed field lines near the light cylinder. Occasional reconnection jets produce high Lorentz factor beams that propagate along magnetic field lines and emit coherent cyclotron-Cherenkov radiation at anomalous Doppler resonance.

field, γ is Lorentz factor of fast particles and s is an integer. The necessary requirement for the anomalous cyclotron resonance is that the refractive index of the mode be larger than unity, and that the parallel speed of the particle be larger than the wave's phase speed. The physics of emission is similar to the Cherenkov process, except that during photon emission a particle *increases* its gyrational motion and goes *up* in Landau levels [9]. The energy is supplied by parallel motion. Importance of anomalous cyclotron resonance for pulsar radio emission has been discussed in Refs. [10, 11, 12].

A curious property of anomalous cyclotron resonance is that cyclotron waves can be emitted at frequencies well below the local cyclotron frequency (recall that in Crab near the light cylinder $\omega_p/\omega_B \sim 2 \times 10^{-3}$). The waves are emitted at the L-O brach (polarized in the $\mathbf{B} - \mathbf{k}$ plane). Its dispersion depends sensitively on the angle of propagation, qualitatively the resonance condition is

$$\omega \sim \frac{|s| \gamma_{\text{bulk}}^3 \omega_B^3}{\gamma_{\text{beam}} \omega_p^2} \quad (2)$$

Note, that for $\gamma \gg (\omega_B/\omega_p)^2$ both the resonant frequency and frequency differences are much smaller than cyclotron frequency.

To reproduce the data, it is required that $r \sim R_{LC}$, $\gamma_{\text{bulk}} \sim 1$, implying that plasma is not streaming (closed field lines), the required density of plasma on closed field lines is much higher, by a factor $\sim 3 \times 10^5$, than the minimal Goldreich-Julian density. Emission is generated by a population of highly energetic particles with radiation-limited Lorentz factors $\gamma_{\text{beam}} \sim 7 \times 10^7$, produced during occasional reconnection close to the Y point, where the last closed field lines approach the light cylinder. The viewing angle with respect to local magnetic field is $\theta = 0.0022$.

The model explains a number of secondary properties of emission bands: (i) that emission bands are not seen below $\sim \text{GHz}$ – the L-O mode exists only above the plasma frequency; (ii) there is a slight drift up in frequencies, but never down (Eilek & Hankins,

priv. comm) – we assume that radiating beam is generated close to light cylinder at magnetic equator, where magnetic field is the lowest; as the beam propagates along magnetic field lines, the local magnetic field increases, leading to increase of resonant frequency, Eq. (2). This is similar to frequency drifts of so called auroras hiss in the Earth magnetosphere [13].

The implications of the model is that closed field lines are populated with dense plasma, exceeding by a factor $10^5 - 10^6$ the minimum charge density. Somewhat surprisingly, the over-density $\sim 10^5$ (with respect to Goldreich-Julian density) we find modeling the generation of Crab giant pulsars, is similar to the over-density required to explain eclipses in the double pulsar.

Magnetospheres of magnetars

Magnetars - strongly magnetized neutron stars - are characterized by powerful persistent and bursting X-ray emission [14], with luminosities well exceeding their spin-down power. Their persistent emission is non-thermal, generally fit with a double black-body or black-body plus power law spectra with a typical photon index of the non-thermal component $\Gamma \sim 2 - 4$. It was suggested by [15] (see also [16]) that large scale currents flowing on closed field lines are driven by twisting of magnetic field lines by the crustal Lorentz stress induced by a tangled magnetic field. These currents results in particle densities much larger than the Goldreich-Julian density *near the stellar surface*

$$n \sim \left(\frac{c}{R_{NS}\Omega} \right) n_{GJ} \gg n_{GJ} \quad (3)$$

(this estimate assumes that poloidal currents create toroidal magnetic field of the same order as poloidal magnetic field and that a typical velocity of charge carries is of the order of the speed of light).

The presence of such a relatively dense plasma was confirmed by [17] through spectral modeling. The presence of a relatively tenuous plasma leads to large magnetospheric optical depths for resonant cyclotron scattering. Due to the large resonant cross-section, the amount of electron-ion plasma that must be suspended in the magnetosphere to produce an optical depth of the order of unity is tiny by astrophysical standards, of the order of 10^9 grams total. Both the emission patterns and spectral properties of the surface radiation are then modified in the magnetosphere, as photons are scattered and their energies are Doppler-shifted in each scatter.

Resonant scattering in *inhomogenous* magnetic field of neutron star magnetosphere has surprising properties which in a simple Schwarzschild-Schuster (back-forth) approximation and for non-relativistic thermal velocities of plasma particles can be investigated analytically. The scattering of a photon with a given frequency ω occurs in narrow resonant layer centered at $\omega_0 = \omega_B$ and a thickness $\sim \beta_T r/3$ (β_T is electron thermal velocity in units of the speed of light). If a surface emission with a given frequency falls on the resonant layer, what are the properties of the transmitted and reflected fluxes? They turn out to be strikingly different from Thomson scattering and from resonant cyclotron scattering in a homogeneous magnetic field (Fig. 3): (i) in the large optical depth limit $\tau \gg 1$

(so that very few photons pass through the layer without scattering), the spectral fluxes of the reflected and the transmitted radiation are equal, so that *a resonant layer with high optical depth is half opaque*; (ii) the transmitted radiation going from high to low magnetic field is *Compton up-scattered* by a factor $\sim 1 + 2\beta_T$, while the reflected waves on average have $\omega \sim \omega_0$; (iii) as optical depth increases, the *transmitted and the reflected fluxes have increasingly narrower distributions*, converging back to δ -functions in the $\tau \rightarrow \infty$ limit.

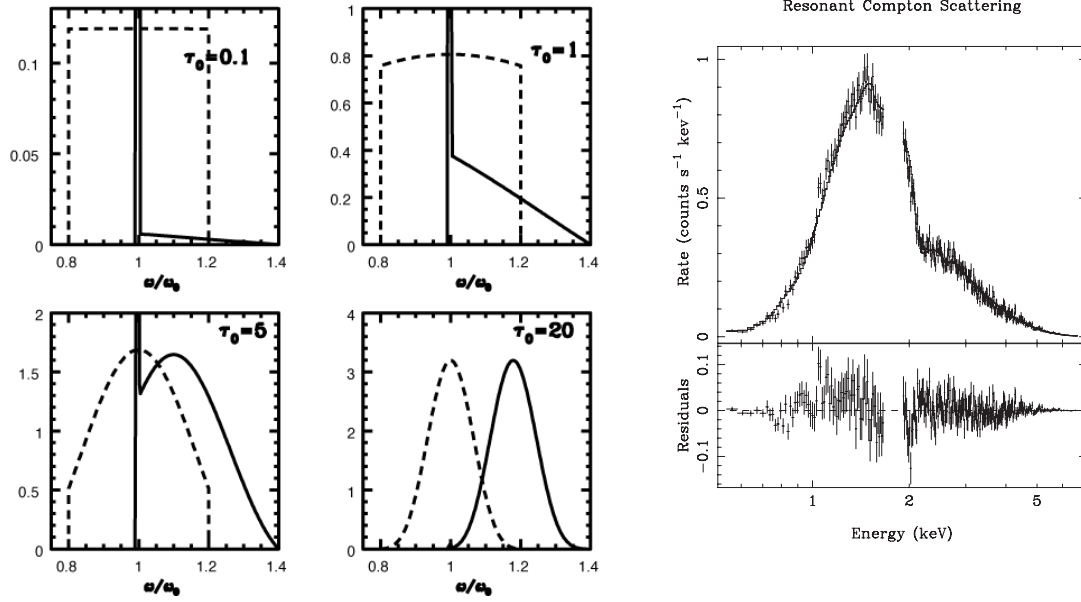


FIGURE 3. (left) Transmitted (solid lines) and reflected (dashed lines) fluxes for a water-bag distribution of particles with $\beta_T = 0.1$ and different optical depths τ_0 . (right) The data fit with the resonant Compton scattering model to X-ray Spectrum of the Anomalous X-ray Pulsar 1E 1048.1–5937

After calculating semi-analytically the transmitted flux for initially Plankian spectra by summing over multiple reflections between resonant layers, we fitted the result to *Chandra* X-ray observatory observation of the anomalous X-ray pulsar (AXP) 1E 1048.1–5937. Our model fares just as well as the “canonical” magnetar spectral model of a blackbody plus power-law model [17]. Most importantly, *the models have the same number of fitting parameters*.

These results were generally confirmed by [18], who applied the model to the XMM-Newton observations of 1E 1048.1–5937. Applications of the model to 1RXS J1708-4009 and SGR 1806-20 are more problematic: these are harder spectra sources, which would require hotter (relativistically hot) plasma, in which case the model becomes inapplicable. In Ref. [19] extensive Monte-Carlo simulations of resonant scattering in neutron star magnetospheres were performed, taking into account relativistic effects and polarization, confirming our results.

DISCUSSION

We have described three very different pieces of evidence indicating that magnetospheres of neutron stars are filled with dense plasma. Are these three facts related? Radio pulsars and magnetars are clearly different: in case of pulsars we are probing plasma density at the light cylinder, while in case of magnetars - near the surface, regions that have substantially different properties. The supply of dense plasma into magnetospheres of magnetars is probably accomplished by unwinding of crustal magnetic field and corresponding twisting of magnetospheric magnetic field [15, 16].

Even radio pulsars seem to be very different: in slow pulsars, like PSR J0737-3039B, plasma can be efficiently trapped on closed field lines by magnetic bottling (for $\sim 10^6$ periods in PSR J0737-3039B, [4]), but not in Crab, where radiative decay times are too short, $\sim 10^{-4}$ sec at the light cylinder [20]. In Ref. [4] it was proposed that high densities on closed field lines of PSR J0737-3039B may be explained by interaction with the wind of the companion, but similar overdensity in an isolated pulsar questions that possibility. Though there are several ways particles can populate closed field lines (*e.g.* kinetic drift from open field lines, pair production by the 'backward' beam from outer gaps), the demands in case of short period pulsars like Crab are pretty high: the mechanism should create an over-density of the order 10^5 with no efficient bottling.

In case of Crab, this over-density is required in a fairly limited region near the light cylinder, where IGPs are presumably produced. It is somewhat natural to associate this density enhancement with the Y-point, where the last closed field line approaches the magnetic equator. In fact, we indeed may expect high density around that region. First, even in rigidly rotating dipolar magnetosphere, the charge density diverges at that point [1]. Second, in case of a more realistic force-free aligned rotator, poloidal magnetic field also diverges at the Y-point [21, 22]. To resolve this divergency, non-ideal effects such as resistivity [22] and/or particle inertia [23] should be taken into account. At the moment, we leave this possibility to further studies.

Finally, though formal similarities between very different physical systems are often superficial and misleading and should be taken with care, we note that closed field lines of the Earth magnetosphere are very active in producing high brightness radio emission like auroral hiss, roars and burst [13].

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